
ENVIRONMENTAL PROBLEMS.
THE PRODUCTION OF LOW-WASTE AND CLOSED
MANUFACTURING SCHEMES

Thermochemical Recovery of Heat Contained in Exhaust Gases of Internal Combustion Engines (A General Approach to the Problem of Recovery of Heat Contained in Exhaust Gases)

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Abstract—The concept of the use of heat contained in exhaust gases of internal combustion engines in order to increase the degree of utilization of the energy contained in engine fuels has been examined. It has been suggested to use heat recovered in such a way for carrying out endothermic reactions of the conversion of alternative fuels. Calculated estimations of the thermal effects of possible reactions and the thermodynamic efficiency of the thermochemical recovery of heat contained in exhaust gases for a reversible thermal power-producing cycle have been performed. A comparison between the effectiveness of the thermal power-producing cycle without the implementation of the stage of thermochemical recovery of heat contained in exhaust gases and that with its implementation has been made. It has been concluded that continuing the research effort in this direction would be appropriate.

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The toxic impact of hazardous components of exhaust gases leaving internal combustion engines on the surroundings and human health is a matter of common knowledge. No less significant is the problem of the transfer of nonrecovered heat into the surroundings and its external irreversible losses that involve unwanted climatic phenomena occurring in large cities. According to the data derived from the external thermal balance of an internal combustion engine, a considerable part of the energy of fuel injected into its cylinders is not utilized in the form of work, but is lost both with exhaust gases and because of dissipation (through the lubrication system, fuel system, etc.) into the surroundings. In engines with a spark-ignition cycle (the Otto cycle), the proportion of irreversible heat losses with exhaust gases alone ranges from 30 to 55%, which corresponds to 12 000–23 000 kJ per kilogram of fuel consumed. In diesel engines, the same component of the energy losses in the thermal balance may amount to as much as 40% [1].

In order to increase the efficiency of using energy contained in fuel, large marine and stationary internal combustion engines are equipped with waste heat recovery boilers for producing steam or hot water. In the engines of automotive and tractor types, the available energy of exhaust gases is partially recovered by means of the use of wave-type pressure exchangers and gas turbines. Research in the field of developing heat recovery circuits for vehicle engines operating on the steam-power Rankine cycle has progressed [1].

The examination of the feasibility of utilizing heat removed from an internal combustion engine together with exhaust gases made on the basis of the principle of thermo-

chemical regeneration is a separate and as of yet poorly known problem. The development of this method is due to studies on the fuel system of engines equipped with thermochemical reactors for preliminary transformation (conversion) of certain types of alternative fuels (in particular, alcohol-based ones) by the action of heat contained in exhaust gases of internal combustion engines. In this work, the authors, within the context of the first law of thermodynamics, analyze the feasibility of reducing the external heat losses associated not with the inherent special features of the operating process of internal combustion engines, but with the imperfection of the assimilation of the chemical energy of fuel outside of the combustion chambers.

The essence of this method of investigating the use of heat contained in exhaust gases is that part of such heat is consumed for organizing the preliminary conversion (provision of the required thermal effect of chemical reactions responsible for this conversion) of initial fuel into another type of fuel with better energy characteristics. Due to this, the corresponding increase in the efficiency of a heat engine as a whole can be achieved. For example, in the catalytic conversion of methanol, heat needed for evaporation is usually taken from the cooling medium, while heat needed for the superheat of methanol and for the conversion process is taken from engine exhaust gases.

In order to obtain conversion products as a new type of fuel with a higher potential of the chemical energy as compared with initial fuel, it is necessary to provide the process of their production on the basis of endothermic reactions with heat supplied from an external source (a heat carrier). In this case, the magnitude of the endothermic effects of

chemical reactions uniquely determines the increase in the energy content of the new type of fuel.

It should be noted that the products of the conversion of a conventional (for example, diesel) fuel obtained in a thermochemical reactor on the basis of the mechanism of exothermic reactions of the incomplete combustion of hydrocarbons have a lower heating value as compared with the initial fuel [3].

The organization of the endothermic cycle of the conversion of hydrocarbons contained in oil fuel on the basis of high-temperature reactions of their conversion using the heat of exhaust gases is a fairly difficult problem to solve. As initial convertible reagents, chemical compounds with a conversion temperature lower than the average temperature level of exhaust gases of the internal combustion engine would be most appropriate for use. It is precisely this that allows one to implement the recovery of heat contained in exhaust gases in order for the endothermic cycle of the conversion of the initial reagents to be provided. To such compounds, a number of light homologues of saturated hydrocarbons (alkanes), lower alcohols, and ethers belong. The selection of the initial reagents is a compromise taking into account the energy value of fuel, the temperature conditions of a process, the spectrum of gases generated while fuel processing, and the cost (see table) [4].

In particular, in the world engine-producing industry, methanol is treated as a very promising alternative fuel.

The use of methanol, besides contributing to the economy of petroleum reserves, makes it possible to considerably reduce the content of toxic components in the combustion products emitted by an engine. Methanol is also the most suitable liquid hydrogen carrier aboard a vehicle. At present, the chemical industry is the main methanol consumer. Methanol belongs to renewable natural energy resources, i.e., there exists a vast raw material base for increasing its production and for the much wider use of it as engine fuel.

Preliminary Estimation of the Endothermic Thermal Effect of a Methanol Decomposition Reaction

The preliminary energy-related estimation of the effect caused by the thermochemical recovery of heat contained in exhaust gases of an engine operating together with the system of methanol conversion can be carried out rather simply on the basis of a comparison between the heating value of liquid methanol and that of the products of its conversion.

The heating value of methanol is 19 670 kJ/kg. Products of the dry conversion of methanol are H_2 and CO contained in the conversion mixture in the ratio of 65% (volume)[12.5% (mass)] to 35% (volume)[87.5% (mass)], respectively. The heating value of the two-component mixture can be defined as

$$H_{if(MCP)} = \sum H_{if(i)} m_i = 0.875 H_{if(CO)} + 0.125 H_{if(H_2)}.$$

Characteristics of the feedstock used for the thermochemical recovery of heat contained in exhaust gases of an internal combustion engine

Feedstock	Cost, USD/kg	Combustion enthalpy, kJ/g	Conversion temperature, K	Content in the mixture, mol %	
				H_2	CO
Methane	0.05–0.1	–50.1	1000	76	17.3
Propane	0.4–0.8	–46.5	700	74	7.2
Butane	–	–45.7	700	74	9.3
Octane	0.6–0.8	–44.7	>1000	70.8	20.4
Methanol	0.15–0.25	–19.7	533	74.4	4.3
Ethanol	0.2–0.3	–26.8	600	73.2	4.3
Dimethyl ether	–	–28.8	533	74.4	4.2

It is known that for carbon monoxide $H_{if(CO)} = 10090$ kJ/kg, while for hydrogen $H_{if(H_2)} = 120\,340$ kJ/kg [1]. Therefore, the heating value of the products of methanol conversion $H_{if(MPC)} = 23\,870$ kJ/kg. Thus, during the combustion of 1 kg of methanol conversion products obtained from the same mass of liquid methanol, the additional heat accumulated in the course of the decomposition of alcohol-based fuel equal to $H_{if(MCP)} - H_{if(M)} = 4200$ kJ/kg will be released.

More than 20% of the available energy of exhaust gases used (utilized) for organizing the endothermic cycle of methane conversion returns to the operating cycle of an internal combustion engine running on methanol conversion products.

The thermochemical principle of the process of regenerating heat energy contained in exhaust gases of the engine reflects the underlying postulates of thermodynamics, in particular, the law of Hess and its corollaries. Let us demonstrate this on the basis of the analysis of the thermal effects of methanol combustion accomplished in accordance with two scenarios (routes). In the first variant, we burn methanol into oxygen:

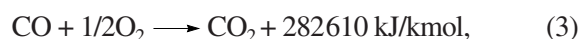


The thermal exothermic effect of this reaction is known and is equal to $Q_1 = 629\,440$ kJ/kmol [1]. As a result of the reaction (1), 3 kmol of combustion products are generated.

In the second, two-stage scenario, alcohol is first dissociated into CO and H_2 :



As this takes place, 1 kmol of CO and 2 kmol of H_2 with the endothermic thermal effect Q_1 are generated. Let us burn in oxygen 3 kmol of products obtained from reaction (2):



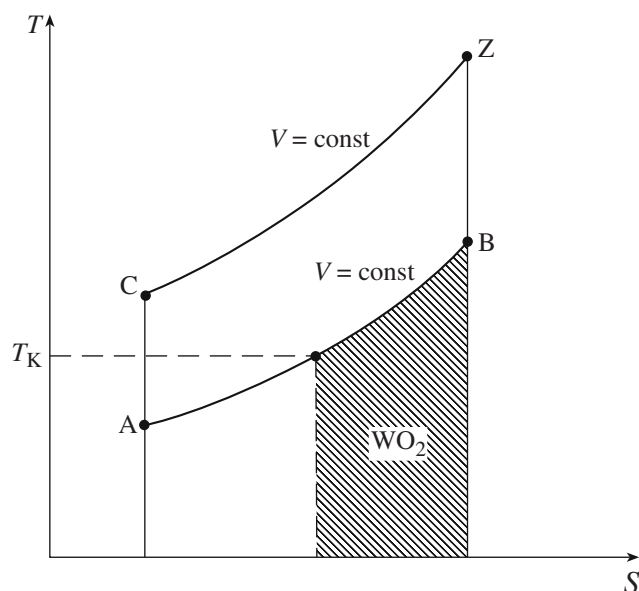


Fig. 1. T-S diagram of an ideal cycle with the thermochemical recovery of heat contained in exhaust gases.

The thermal effects of reactions (3) and (4) are given according to data borrowed from [5]. The total thermal effect of these two reactions is equal to $Q_{3-4} = 764000$ kJ/kmol (in an elementary reaction of hydrogen oxidation two of its molecules take part, and this will result in the doubling of the total thermal effect).

According to the first and the second scenarios of methanol oxidation, the initial and end states of the system (its amount and composition) are the same: initial state, 1 kmol of CH_2OH ; end state, 1 kmol of CO_2 and 2 kmol of H_2O . In this case, in complete agreement with the law of Hess, the total thermal effects of various routes of methanol oxidation should be the same: $629\,440 = -Q_2 + 764090$ kJ/kmol. Hence, $Q_2 = 134\,650$ kJ/kmol.

Heat Q_2 corresponds to the thermal effect (corollary 2 from the law of Hess) of reaction (2) of methanol dissociation.

An analysis showed that the thermal effect of burning a converted mixture (methanol conversion products) of CO and H_2 (synthetic fuel) exceeds the effect of burning the same amount of nonconverted methanol (initial fuel) by a value of $Q_2 = 134\,650$ kJ/kmol, which corresponds to the amount of energy expended for alcohol decomposition. Under operation conditions of devices used for the thermochemical recovery of heat of engine exhaust gases, this value is adequate to the heat taken (recovered) from the energy of the flow of exhaust gases that previously had been released into the atmosphere.

Efficiency of the Thermochemical Recovery of Heat Contained in Exhaust Gases

It follows from the aforementioned that the application of a system of preliminary decomposition of alcohol-based fuel for feeding an internal combustion engine makes it possible to increase the efficiency of the use of the chemical energy of fuel due to waste heat recovery. In this case, the operating process of an internal combustion engine is implemented on the basis of the regenerative thermodynamic cycle. For example, for engines with a spark-ignition combustion cycle (the Otto cycle), the reversible thermodynamic cycle with waste heat recovery can be represented by a T-S diagram shown in Fig. 1.

As is evident from the diagram, the degree of thermal recovery W can be written in the following way:

$$W = Q_r/Q_2 \quad (5)$$

where Q_r is amount of heat recovered to the cycle;

$$Q_r = M_2 \Omega C_V (T_B - T_K);$$

Q_2 is $M_2 \Omega C_V (T_B - T_K)$; and

M_2 and ΩC_V are the amount (mass) of the working medium and its average molar heat capacity at a constant volume, respectively.

We can end up with

$$W = \frac{T_B - T_K}{T_B - T_A}. \quad (6)$$

As follows from expression (6), the degree of heat recovery W depends on the temperature of the conversion process T_K and increases with its decrease.

It should be noted that modern catalysts of methanol conversion allow to for the implementation of the process at operating temperatures no lower than $280\text{--}300^\circ\text{C}$ [5], thereby determining the minimum possible temperature limit of exhaust gases of an internal combustion engine at which the organization of this process would be feasible. It is obvious that these requirements imposed on the temperature level of exhaust gases of the engine can only be met within a certain range of variation of modes of its running regime, primarily in the region of average and high temperatures. Therefore, as of today, one can speak of the mere possibility of the partial recovery of heat contained in exhaust gases of an engine on the basis of the method under consideration.

A preliminary analysis shows that depending on the conditions of the organization of the methanol conversion process and selection of a catalyst, about 10–15% of irreversible external losses of heat contained in exhaust gases can be returned to the operating cycle of the engine in the case when the method of thermochemical recovery is used. The problem of the fuller recovery of the heat of exhaust gases for conventional engines can be solved by developing highly efficient low-temperature catalysts of methanol conversion and specific tools used for the rapid startup of the thermochemical recovery unit.

Effect of the Thermochemical Recovery of Heat of Exhaust Gases on the Thermal Efficiency of a Heat Engine

Let us consider the question stated here under the theoretical aspect. It is well known that the conversion of chemical energy stored in engine fuel into work performed in internal combustion engines is carried out in two stages: at the first stage, chemical energy is transformed into heat, and only at the second stage is this heat implemented in the form of work that then is utilized by the end user.

It is during the course of these transformations that the main losses of the available energy of fuel occur, which would make the engine operation less efficient. As pointed out above, the level of these losses is high, and for various types of internal combustion engines it may amount to as much as 50–75% [1].

In order to increase the efficiency of using the chemical energy of fuel, it is necessary to develop methods of reducing its losses both at the first stage of transformation and at the second stage. On the basis of the level of investigations achieved in this field, it is to be noted that until the present time in the engine-production industry (as in the machine-production industry on the whole), a very efficient method of reducing losses of the fuel performance at the second stage of energy conversion was implemented based on classical postulates of thermodynamics. The essence of this method stems from the correlation between the average temperatures of supply T_{lav} and removal T_{2av} of the heat of the reversible cycle (Fig. 2):

$$T_{1av} = \frac{\int T ds}{S_I - S_{II}}; \quad T_{2av} = \frac{\int T ds}{S_I - S_{II}}.$$

The thermal efficiency of the cycle $a-b-c-d-a$ is

$$\eta_T = 1 - T_{2av}/T_{1av} \quad (7)$$

i.e., the higher the average temperature of heat supply at the considered level of the average temperature of heat removal, the higher the thermal efficiency of the cycle.

However, in modern internal combustion engines, the temperature level of the heat content of the working medium at initial parameters is such that at its increase, the thermal breakdown of the material of walls making the displacement volume of an engine occurs. Therefore, an increase in the efficiency of using fuel in a heat engine by means of an increase in the average upper thermodynamic temperature of the working medium in the cycle depends on the possibilities for a further increase in the high-temperature strength and heat resistance of the structural materials of the combustion chamber components. When one considers that for most conventional materials these possibilities have already virtually been exhausted, it becomes evident that the very method involving an increase in the working medium temperature shows little promise.

In the connection with the aforementioned, it seems advisable to develop a method of lowering the level of irreversible losses that occur at the first stage of conversion of

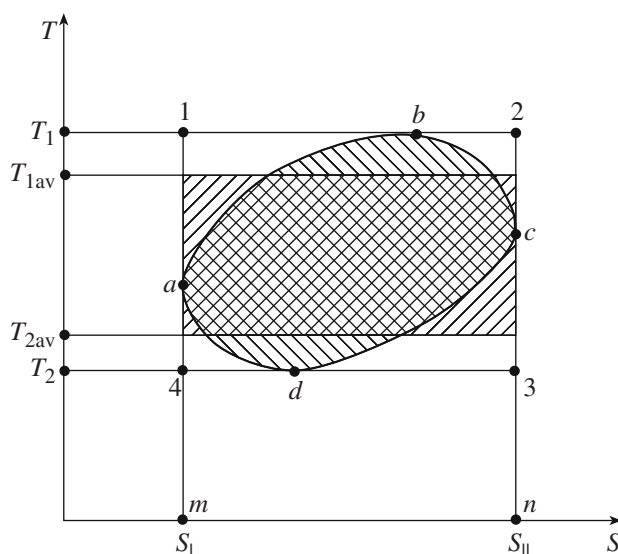


Fig. 2. T - S diagram of a heat engine (reversible) cycle.

chemical energy contained in fuel, i.e., at the stage of its conversion into heat. In this case, the implementation of this method, wherever possible, should not involve an increase in the fuel combustion temperature.

On the basis of the main postulates of chemical thermodynamics [6], one can assert that the implementation of such a method is a priori possible only when there are fuels whose combustion at the same temperature would be accompanied by different levels of irreversible losses. To such a category, the following fuels can be assigned:

- (a) most fossil fuels (coal, petroleum, natural gas) and
(b) a number of other compounds that offer a high level of irreversible losses when burned and that can be, by means of thermochemical transformations, converted into new (artificial) fuels (for example, synthesis gas, a mixture of hydrogen and carbon oxide).

The transformation of the chemical energy of such an artificial fuel into heat involves lesser irreversible heat losses. The practical implementation of such a method of thermochemical transformation can be accomplished using endothermic reactions of the conversion of alternative fuels with the supply of an appropriate amount of heat. For the first time, a scientific-methodical substantiation of this method and its practical implementation as applied to large commercial power plants were made by V.G. Nosatch [7] (Ukrainian Research Institute of Engineering Thermophysics).

Since the method presupposed the necessity for using the process of endothermic conversion of hydrocarbon fuel based on the cycle of thermochemical conversion of hydrocarbons, it has been called the “thermochemical method of heat recovery” [7]. The method has been developed on the basis of the fundamental concepts of thermochemistry and can be implemented for any type of a heat engine, including internal combustion engines.

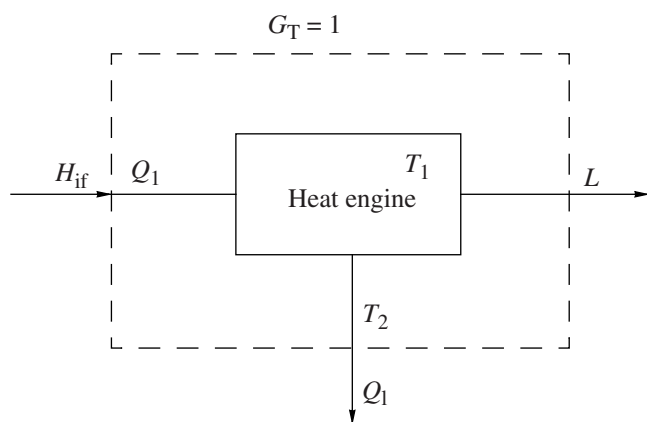


Fig. 3. Schematic diagram of a heat engine without the recovery of heat contained in exhaust gases.

As follows from the definition of the method of thermochemical heat recovery, in the operating cycle of a heat engine one more process is provided. While in a common engine the chemical energy of fuel is transformed into heat in one stage, here the transformation takes place in two stages. At the first stage, the converted fuel is burned at a higher energy level. The presence of two stages of energy conversion, in the course of which heat removed from the cycle is used, makes it possible to increase the efficiency of the use of energy contained in the initial fuel in a thermal power engine.

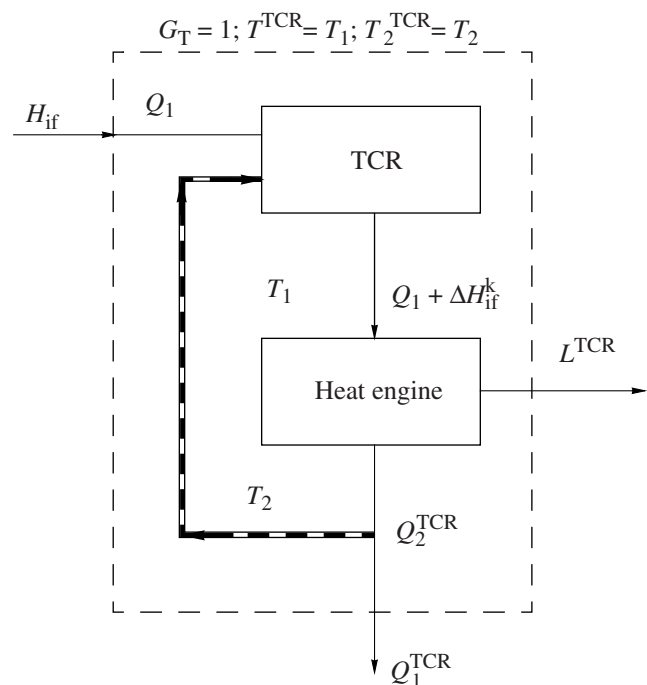


Fig. 4. Schematic diagram of a heat engine with a unit for the thermochemical recovery of heat contained in exhaust gases.

In the general way, the efficiency of thermochemical heat recovery depends on the type of heat engine, the method and conditions of the organization of the operating process in it, as well as of the type of initial fuel (the total endothermic effect of the system of reactions of its conversion).

Comparative Analysis of the Efficiency of Implementing Heat Engine Cycles with and without Thermochemical Heat Recovery

As an illustration of the feasibility of increasing the efficiency of the use of the chemical energy of fuel, let us perform a comparative analysis in which we compare the possibilities of converting the energy of fuel in two heat engines similar from the viewpoint of energy. The first of them (Fig. 3) operates according to the conventional scheme; the second engine (Fig. 4) operates using thermochemical heat recovery. The required thermal conditions of the fuel conversion process are provided due to the supply of heat from branches of the heat engine cycle, i.e., with the use of heat contained in exhaust gases.

The first engine operates in the following way. Initial fuel having parameters of the surroundings is supplied into the heat engine and burned there. The process of burning is accompanied by a release of heat equal to the heating value (combustion heat) of fuel $Q_1 = H_{if}$ (in the analysis, the mass of fuel is taken as unity). This heat is transferred to the working medium of the heat engine. In order to make the analysis simpler, let us consider the heat transfer as occurring at the average upper temperature T_1 . Once the cycle has been completed, the combustion products are released into the atmosphere.

In such an idealized heat engine heat equal to H_{av} at an average upper temperature T_1 is transferred to the working medium. If the average lower temperature of the latter at which the removal of heat takes place is equal to T_2 , the work done by the medium is

$$L = Q_1 - Q_2 = H_{if} - H_{if}(T_1/T_2) = H_{if}(1 - T_1/T_2). \quad (8)$$

In this case, the efficiency of the use of chemical energy contained in the fuel can be defined as

$$\eta = L/H_{if} = 1 - T_1/T_2 \quad (9)$$

Dependence (9) defines the efficiency of the heat engine that is equal to the ratio of the amount of energy released in the form of work to the total amount of energy brought into the heat engine. Let us note that the expression for the efficiency of the idealized heat engine being considered, whose schematic diagram is given in Fig. 3, is the same as the thermal efficiency of the cycle. This points to the fact that in the heat engine without thermochemical regeneration, the efficiency of the use of fuel energy depends completely on the conversion of heat into work and cannot be higher than the heat conversion efficiency.

The schematic diagram of a second heat engine whose schematic diagram is shown in Fig. 4 operates using the principle of the thermochemical recovery of heat contained

in exhaust gases. Unlike the previous heat engine, fuel is not supplied to this heat engine immediately, but first passes through the stage of thermochemical processing in a special apparatus—a thermochemical reactor. Here, under the action of heat coming from heat-removing branches of the heat engine cycle, at the average lower temperature T_2 , the thermochemical conversion of the initial fuel into a converted one takes place, and this converted fuel is fed into the heat engine for combustion. If we let the heat exchange in the heat engine equipped with a thermochemical reactor to be performed reversibly (as by the analysis of the first option), then the working medium of the heat engine equipped with a thermochemical reactor should at the average upper temperature T_1 gain heat equal to the heating value of converted (artificial) fuel: $Q_1^{\text{TCR}} = H_{\text{if}}^*$.

Consequently, in this case heat received by the working medium exceeds the heating value of initial fuel H_{if} by the amount $\Delta H_{\text{if}}^{\text{K}}$, that was absorbed during the thermochemical conversion of initial fuel in the reactor and, correspondingly, is equal to

$$H_{\text{if}}^{\text{K}} = H_{\text{if}} + \Delta H_{\text{if}}^{\text{K}}. \quad (10)$$

Let us consider the heat engine with the thermochemical reactor as converting heat absorbed by the working medium with the same efficiency as the heat engine without the thermochemical reactor, i.e., the thermal efficiencies of both engines are the same. Then, the work that can be performed by the heat engine with the thermochemical reactor will be

$$L^{\text{TCR}} = (H_{\text{if}} + \Delta H_{\text{if}}^{\text{K}}) (1 - T_2/T_1). \quad (11)$$

The efficiency of using fuel energy in the heat engine with the thermochemical reactor is defined by expression

$$\begin{aligned} \eta^{\text{TCR}} &= L^{\text{TCR}}/H_{\text{if}} = (H_{\text{if}} + \Delta H_{\text{if}}^{\text{K}})(1 - T_2/T_1)/H_{\text{if}} \\ &= H_{\text{if}}(1 - T_2/T_1)/H_{\text{if}} + \Delta H_{\text{if}}^{\text{K}}(1 - T_2/T_1)/H_{\text{if}} \quad (12) \\ &= \eta_T + (\Delta H_{\text{if}}^{\text{K}}/H_{\text{if}})\eta_T = \eta_T(1 + \Delta H_{\text{if}}^{\text{K}}/H_{\text{if}}). \end{aligned}$$

It follows from (12) that the efficiency of the conversion of chemical energy in the cycle with the unit for the thermochemical recovery of heat contained in exhaust gases, as compared with its conversion in a conventional heat engine, can be increased by $(1 + \Delta H_{\text{if}}^{\text{K}}/H_{\text{if}})$ times.

A Practical Example of the Implementation of Heat Engine Cycles with Thermochemical Heat Recovery

If we know the heating values of the initial and converted fuels and estimate the endothermic effect of the conversion reaction equal to the amount of heat removed from heat-releasing branches of the heat engine cycle (recovered heat of exhaust gases) from the difference of these values, then we shall be able to estimate the degree of the increase in the thermal efficiency of a heat engine owing to the use

of the thermochemical recovery of heat contained in exhaust gases.

Let us demonstrate this by the example of a hypothetical heat engine with thermochemical heat recovery burning alcohol fuel, say, methanol [8]. Liquid methanol has the heating value $H_{\text{if}} = 19\,670$ kJ/kg. The heating value of methanol conversion products (converted fuel), as was shown above, corresponds to $H_{\text{if}}^* = 23\,870$ kJ/kg. Hence, the thermal thermochemical effect of the methanol conversion reaction (amount of heat recovered from exhaust gases) is equal to 4200 kJ/kg. Taking arbitrarily the value of the average upper temperature of the cycle to be $T_1 = 2000$ K and the average lower temperature to be $T_2 = 1000$ K, we obtain the value of the thermal efficiency of an ideal heat engine without thermochemical heat recovery $\eta_T = 50\%$. For a heat engine with the thermochemical heat recovery of waste heat, according to (12), it will exceed the efficiency of the former heat engine by $(1 + 4200/19\,670) = 1.21$ times, i.e., it will turn out to be $\eta_T^{\text{TCR}} = 60.5\%$.

From the previously cited analysis, it follows that in the case of using the method of thermochemical recovery of heat contained in exhaust gases, irreversible external losses in the course of the conversion of chemical energy contained in fuel into heat are always less than the corresponding losses during direct fuel combustion without its preliminary thermochemical processing. As this takes place, the value of reducing irreversible losses is exactly equal to the work that should be expended to compensate for the total heat endothermic effect of the reaction of initial fuel conversion.

The practical implementation of the method of thermochemical recovery for conditions of the operating cycle of an internal combustion engine with spark ignition suggests that as an initial fuel, it would be appropriate to use chemical compounds with relatively low temperatures of reactions of conversion and dissociation (alcohols, ethers, etc.), the gaseous products of which (converted fuel) can be used as the main fuel for the engine (an analogue of a gas engine).

It should be noted that in this case, the recovery efficiency cannot be implemented to the full extent for certain operation modes of the internal combustion engine because of the temperature difference (in the range less than 300°C) of exhaust gases (heating agent) and the difficulties in supplying the required heat to the reaction zone to maintain the preassigned thermal conditions of the endothermic conversion process during the discharge of the complete mass of initial fuel through the reactor.

When this happens, in principle, the possibility of implementing the method of thermochemical recovery of heat of exhaust gases in fuel systems of diesel engines in which diesel fuel is the main fuel burned, while for the organization of the conversion process an additional fuel with a low conversion temperature is burned, is not ruled out. In this case, the discharge of additional fuel through the reactor can be varied according to the temperature and energy capabilities of a heat carrier (exhaust gases) for each

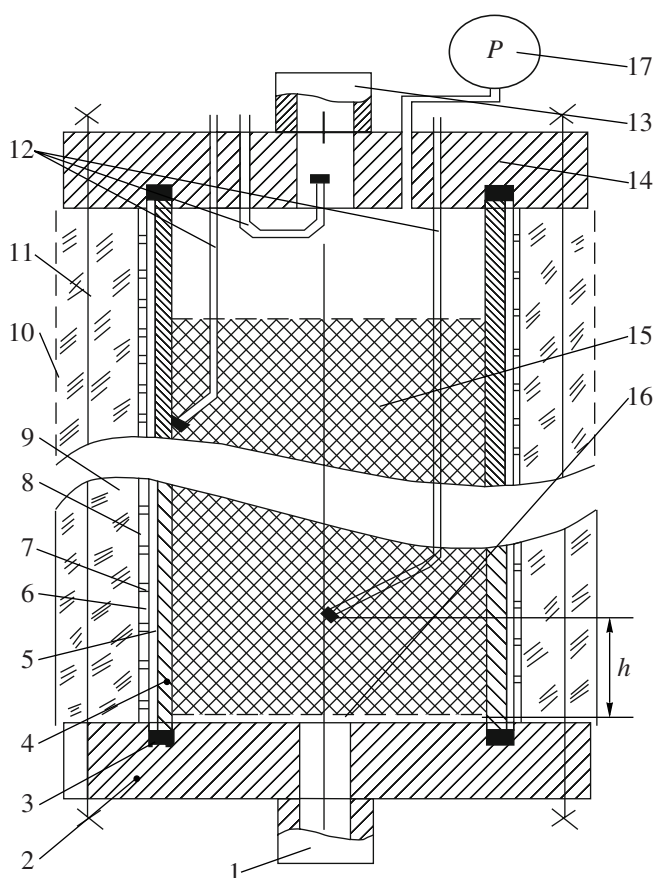


Fig. 5. Heterogeneous catalytic reactor used for the steam conversion (hydrolysis) of methanol: (1) inlet port (brass); (2) lower flange (stainless steel); (3) gasket (fluoroplastic); (4) reactor vessel (stainless steel); (5) asbestos gasket; (6) electric insulation (mica); (7) electric heating element; (8) siliceous tape; (9) layer of kaolin felt; (10) glass fiber tape; (11) tie rod with nuts; (12) thermocouples (chromel-alumel); (13) outlet port (brass); (14) upper flange (stainless steel); (15) catalyst; (16) catalyst grid (mesh); and (17) standard pressure gage.

specific mode of engine operation on the basis of ensuring the total completion of the conversion of initial (auxiliary) fuel. Such fuel systems of diesel engines in modern research practice still remain poorly known. However, they are of certain interest, primarily from the viewpoint of the estimation of a potentially possible level of the efficiency of using thermochemical conversion as a part of diesel engine fuel systems. These questions call for separate scrutiny.

It should be noted that the implementation of the above-mentioned method of the recovery of heat contained in exhaust gases for the case of heat engines seems to be very promising. By virtue of the technical simplicity of this method, its implementation requires neither serious engineering developments nor substantial investments. The basic component of the fuel conversion system (the reactor) is the simplest design of a heat-exchange reactor (a chemical analogue of a tubular heat exchanger) whose tube space is filled by a granulated (in the future, by an applied planar)

catalyst. The authors have developed in practice the technological aspects of the implementation of a catalytic reactor for methanol steam conversion (hydrolysis) using a model facility whose core was the electrically-heated laboratory-scale flow reactor shown in Fig. 5 [9]. The catalyst consisted of granules of the solid zeolite carrier Na-X impregnated by an oxidic copper-chromium-zinc composition. The experimental data obtained make it possible to design an entire family of prototype reactors for various types of heat engines, fuel, and exhaust systems. The mass and dimensional characteristics of the reactor (the size of a common automotive exhaust muffler) provide the convenience of its installation in the engine exhaust system.

In addition, in its effect on the performance of a heat engine, this method exhibits the property of multifunctionality. The method that has initially been directed to the improvement of the characteristics of the thermodynamic and, hence, the operating cycle of the internal combustion engine, at the same time provides a possibility for improving the energy and ecological characteristics of the heat engine owing to the fact that a hydrogen-containing component forms a part of the fuel blend [3]. This method allows also one to make a partial replacement of conventional oil fuels by alternative energy carriers obtained from renewable raw sources, thereby contributing to the solution of the energy conservation problem.

NOTATION

- ICE—internal combustion engine;
- FG—exhaust (flue) gases;
- MCP—methanol conversion products;
- HE—heat engine;
- TCR—thermochemical recovery (thermochemical reactor);
- L —work;
- H —heating value;
- ΔH —heating value difference;
- Q —thermal effect of the chemical reaction (amount of heat);
- T —temperature;
- M and ΩC_V —amount (mass) of the working medium and its average molar heat capacity at a constant volume, respectively;
- QW—degree of thermochemical heat recovery;
- η —efficiency.

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